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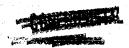## THE PHYSICS OF DIELECTRICS IN THE USSR

G. I. Skanavi

Engineering physics was developed in the USSR only after the great October Socialist Revolution, when vigorously growing socialist industry needed new and independent roads of development. This is especially true of the new branch of physics closely connected with the technique of electrical insulation -- the physics of dielectrics.

Credit must be given to Soviet physicists for being the first to begin a comprehensive study of the processes which take place in dielectrics under the influence of an electrical field. Such a study is not of scientific interest alone but is absolutely essential for rational selection and synthesis of elec- trical insulating materials.

At present, the results of the labor of Soviet scientists in the field of dielectrics make it possible, first, to analyze in a number of cases complex processes which occur in dielectrics placed in an electrical field; second, to calculate certain more important dielectric constants from other constants, link- ing the basic electrical properties of dielectrics with their molecular structure; and third, to correct, at frequent intervals, the work of chemists and technicians in the construction of new high quality dielectrics possessing the necessary special properties.

The attainments of Soviet dielectrical physics significantly facilitated the development of insulating techniques not only with respect to selection and syn- thesis of insulating materials, but also in constructing and designing commercial insulators and condensers, and permitted the finding of new independent methods for solving practical problems.

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A. Ionic Conductivity of Dielectrics

In 1922 - 23, work was begun by Soviet scientists in the field of dielectrics, and some of their investigations were published in world literature. Certain problems were clarified concerning dielectric polarization, electrical conductivity and rupture of gaseous dielectrics, dielectric polarization and dielectric losses of polarized liquids, and others. Electrical characteristics of solid dielectrics, which are most important from the viewpoint of insulation techniques, were almost neglected. The individual experimental facts were known; these related basically to the so-called "dielectric anomalies" -- a reduction of the current in a solid dielectric as time passes, with a constant voltage and, in connection with this, the apparent nonconformity with Ohm's law.

Soviet physicists, under the leadership of A. F. Ioffe who started this work, dealt, first of all, with the study of conductivity of solid dielectrics. A series of new experimental facts and rules were established which permitted the explanation in a general way of the nature of the conductivity of solid dielectrics and the causes for the apparent nonconformity with Ohm's law. Later, these works were greatly expanded and, at present, the nature of dielectric conductivity is significantly clearer.

The conductivity of the greater portion of dielectrics, under conditions well below the rupture point, is essentially of an ionic type. This was clearly shown by a series of investigations devoted to a verification of Faraday's law. For ionic crystals, glass, lacquered films, etc., it was shown (Pruzhinino) that Faraday's law is well substantiated. At the same time, the classical method of verifying Faraday's law, established by Tuband for crystals, was developed and modified for use in commercial insulation materials (glass, lacquered films, mica). The mechanics of ionic conductivity of nongaseous dielectrics, due to the work of Ioffe, Frankel' and others, can now be treated from a single point of view.
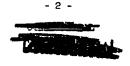
Weakly attached ions in dielectrics, (for example, in crystals -- an ionic lattice, in glass -- ions which are found in loose structural packing, etc.), undergoing thermal agitation can move gradually from one "potential pocket" to another. Each ion in such a transfer overcomes a certain potential barrier, depending on the structure of the dielectric. At the same time, the kinetic energy of the ion is spent in work of overcoming this barrier -- the work of activation. Even in a liquid dielectric, similar thermal agitation of the ions can take place. The ion adheres to the molecule, enters into its group of atoms and is thereby attached to it, finding itself in a potential pocket.
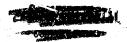
However, the ion taking part in the thermal agitation has a certain probability of breaking away from the molecule. In breaking away, the kinetic energy of the ion is used in working against the cohesive force of the molecule -- the work of activation. The activation energy, inherent in the ion, is found not only in a solid but also in a liquid body. After moving some distance along a "free path," the ion again falls into a potential pocket. With the application of an external electrical field, activated ions are carried in the direction of the field. The average velocity of the ion in the direction of the field, with small fields, is directly proportional to the field intensity.

Because of this, the conductivity of any nongaseous dielectric can easily be found with the aid of the expression for mobility with constants which characterize the molecular structure of the dielectric. It can be expressed in the following way:

$$\gamma = nq\chi \frac{nq^2\delta^2\nu}{6kT} e^{-\frac{U}{kT}},$$

where ν equals natural oscillation frequency of the ion at the place of attachment, n equals the number of ion-carriers of current in a cm^3, q equals charge of the ion, χ equals mobility of the ion, δ equals mean free path, U equals activation energy, kT equals energy of thermal agitation. For liquid dielectrics it is easy to link the conductivity with the macroscopic characteristic of the liquid-viscosity.

The viscosity of the liquid is dependent on the motion of the molecules, which can be treated in the same way as the motion of ions. While flowing, i.e., the motion of liquid layers, the molecules are subjected to the action of certain forces. The regulated motion of the molecules under the action of this force also determines the viscosity of the liquid.

This analogy permits the establishment of a relationship between the conductivity and the viscosity of the liquid, i.e., it clarifies the long-known experimental law of Val'den by which the product of the conductivity and viscosity is constant for a given liquid dielectric and does not depend on the temperature. The dependence of ionic conductivity of nongaseous dielectrics on temperature, in accordance with the facts set forth, must have the following form:

$$\gamma = A e^{-B/T}$$

The coefficient A is comparatively independent of the temperature. If various types of ions can move in a dielectric, or the same type ions but attached in varying degrees, then

$$\gamma = \sum_{i=1}^{i=N} A_i e^{-B_i/T}$$

This dependence was experimentally established by Kobeko, Kuvshinskiy, Shishkin, Lazarev, and others for a great number of gaseous dielectrics; the right side of the equation consists sometimes of two terms and sometimes of one.

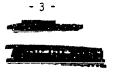Thus, ionic conductivity of nongaseous dielectrics is sufficiently clear in a general way.

The question of precisely what kinds of ions move in the dielectric while current flows, also served as a subject for research by Soviet physicists. It was established that in liquid nonpolarized dielectrics used for the entire insulation (transformer and vegetable oil, solvents for insulating lacquers -- benzol, toluene, xylene, etc.), the basic carriers of the current appear to be ions of admixtures -- contaminated. In crystalline dielectrics, light and relatively weakly attached ions of alkali metals move first. A break in the curve $\lg \gamma = f\left(\frac{1}{T}\right)$, found for simpler ionic crystals (of the type $NaCl$) served for a long while as the subject of a lively discussion. A school of thought led by Smekal took the position that the conductivity of these crystals can be divided into two parts: defective conductivity which dominates at low temperatures, and the correct conductivity which takes place only at high temperature. Defective conductivity is caused by the motion of ions in the defective places -- distortion of the crystal lattice which must obviously exist in every crystal. Smekal considered this the decisive factor in defective conductivity.

Soviet physicists, however, (Gokhberg and others) showed experimentally, in work devoted to explaining the mechanism of crystal conductivity, that the deciding factor was considered to be defects in the lattice only because the crystals were poorly cleaned and their conductivity depended on contaminated ions.

Frenkel's work in 1926 was the first theoretical investigation of the natural conductivity of crystals.

At present, it can be considered as established that there are two possible basic explanations of ion transfers in crystals, namely, (1) transfer of ions between the units with a further movement in the interlattice space, and (2) the jump from one unit to another -- unoccupied unit (movement of "gaps").

The predominance of one type of movement or another is explained on the basis of appraisable calculations of corresponding differences in energy. For alkaline-halide crystals it has been established that the most probable is the gap mechanism of conductivity.

The conductivity of crystals at low temperature depends to a great degree on the presence and nature of admixture. Admixed ions are generally more weakly attached than the basic lattice ions since they are located, for the most part, either in inter-lattice space or in defective spots. Only with a gap type of conductivity can a small quantity of admixture ions be located in unoccupied lattice units and (due to the high degree of attachment) without causing a noticeable increase of conductivity.

It is very difficult to isolate experimentally the motion of admixed ions from that of basic lattice ions at the defective place. In connection with this, the conductivity mechanism presented by Smekal, even if it could take place, is by no means the only possibility.
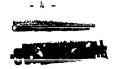
A good deal was done by Soviet physicists in studying the conductivity of glass, Shukarev, Myuller, Markin, and others. In pure glass having only one vitreous oxide, there are no ions whose movement would allow conductivity. Actually, the conductivity of such glass is nearly negligible. Commercial glass has a complex composition. Besides the vitreous oxide, it contains other oxides of alkaline and alkaline-earth metals whose presence determine the necessary physical-chemical and technological characteristics of the glass. The conductivity of commercial glass is primarily determined by the presence of alkaline metals.

If, in the composition of the glass, there is introduced an oxide of a single-valence metal (Na_2O, K_2O), then, in the formation of the glass, an atom of oxygen of the oxide combines with an atom of silicon or boron and occupies one of the apexes of the elementary nucleus. The atom of the alkaline metal, having only one valence tie, connects with only one atom of oxygen. As a result of this, at the place where the atom of the single-valence metal is located, a disintegration of the structure occurs since it has no possibility of combining with another atom of oxygen, maintaining the network. The disintegration of the structure is shown by the fact that a region of increased potential energy forms around the atom of the single-valence metal. Thus the introduction of an oxide of a single-valence metal causes (1) the disintegration of the structure of the glass, and (2) the presence of weakly attached atoms (or ions) of the single-valence metal. Both these factors greatly increase the conductivity of glass.

The introduction of bivalent metallic oxides (for example, CaO, BaO, etc.) not only does not increase but can even decrease the conductivity of the glass. The atom of bivalent metal, due to the second tie, can combine simultaneously with two atoms of oxygen. Thus, in the structural network of the glass, disintegration will not take place. It can also happen that the bivalent metallic atom will join the ends of the disintegrated network and eliminate the looseness of structure of the pure glass. A systematic study of the influence of the composition of glass on its conductivity was conducted by Soviet physicists. As a result of their work, not only were the above-mentioned viewpoints established but also a series of interesting experimental data was obtained which permitted a rational approach to the selection of the desired type of glass.

Soviet physicists, even in the first years after the revolution, gave special attention to the secondary appearances which are related to the passage of a current through a solid dielectric at low temperatures and which were especially puzzling for a long time. The matter concerns the reduction, with time, of current passing through a dielectric with a constant applied voltage, and the deviation from Ohm's law. The effect was discovered more than 50 years ago by Pierre Curie. The work of the Soviet physicists managed to clear up its character to a remarkable degree.

Twenty-five years ago A. F. Ioffe, in his investigations on quartz, laid the foundation for the physics of dielectrics, particularly in studying current decrease in solid dielectrics and effects related to it. In this investigation he was the first to understand the high-voltage polarization of solid dielectrics and was drawn to an explanation of the possibility of accumulation of space charge in a solid body.

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At present, due to the work of Gokhberg, V. A. Ioffe, Sinel'nikov, Venderovich, and others, there is a possibility of dividing solid dielectrics, according to the nature of the current decrease, into a series of types:

First type--Crystals with a high degree of symmetry; in clear crystals, in the absence of defects in the crystal lattice, current decrease does not take place and the distribution of potential is linear.

Second type--Crystals of the calcite and saltpeter type: an abrupt drop in current with time; space charge distributed mostly in a thin layer at the cathode.

Third type--Crystals with a low degree of symmetry (quartz, mica); a significant drop in current with time, with a very complex distribution of the space charge, and possible molding.

Fourth type--Amorphous and ceramic dielectrics: the drop in current occurs in very short time periods (the establishment of dielectric polarization), and also at high temperatures (molding): the drop in potential is centered basically in the molded layer.

Fifth type--Nonuniform dielectrics (commercial laminated insulating materials): the drop of current is related to the accumulation of charge on the surfaces of the nonhomogeneous material (the classical Maxwell case).

By Ioffe's work it was shown that if the electromotive force of polarization, which arises due to the accumulation of space charge, is calculated, then the resistance of the dielectric in weak fields is independent of the voltage.

Actual deviation from Ohm's law in solid dielectrics begins in very strong fields.

Following the reasoning on the mechanism of ion movement in a dielectric, discussed above, it is not difficult to obtain an expression for the current density in a nongaseous dielectric in strong fields, i.e., in those cases when the work of the field along the free path is equal to the energy of thermal agitation:

$$j = \frac{n}{6kT} \nu q^2 \delta^2 e - U/kT \left(E + \frac{q^2 \delta^2 E^2}{24 k^2 T^2} - \ldots \right)$$
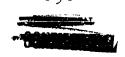
(The same designations as above).

The density of the current is no longer proportional to the voltage of the field but instead depends on it according to a complex law; the conductivity increases with an increase in the field voltage, which agrees qualitatively with Ful's known experimental law.

In strong fields (for glass, for example, higher than $2 \cdot 10^6$ volts/cm), electronic conductivity, which is negligible in weak fields for most dielectrics, is superimposed on ionic conductivity.

The temperature coefficient of conductivity changes in strong fields. This follows from the expression for ionic conductivity

$$\gamma = j/E = \frac{n}{6kT} \nu q^2 \delta^2 e - U/kT \left(1 + \frac{q^2 \delta^2 E}{24 k^2 T^2} + \ldots \right);$$

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As is clear from this expression, the conductivity, as the voltage of the field increases, begins to depend less on the temperature.

Besides, the electronic conductivity which appeared in strong fields has a different temperature coefficient than the ionic conductivity.

The question of electronic conductivity of dielectrics in strong fields is closely connected with the electrical breakdown of dielectrics. See below.

The dependence of electronic conductivity on the voltage of the field was first exposed in the theoretical work of Ya. I. Frenkel.

B. Dielectric Polarization and Losses

The vast amount of work by Soviet physicists in the area of dielectric polarization and losses can be divided as follows:

The study of abnormal polarization of Rochelle salt and piezoelectricity;

The study of dielectric polarization and losses of polycrystalline dielectrics; the discovery of a new type of polarization in barium titanate;

The study of dielectric polarization and losses of amorphous dielectrics and high-molecular weight compounds, which was developed subsequently into an elaborate investigation dedicated to the study of amorphous compounds;

The study of dielectric losses and polarization of glass and ceramic materials with the practical objective of obtaining new high-quality insulating materials; these projects are closely tied in with the work of Soviet chemists, technicians and engineers in the study of dielectric losses of a great number of commercial insulating materials (oil, lacquers, various compounds, fibrous materials, plastics) which will not only permit the development of new materials but the improvement of known materials as well;

The study of dielectric characteristics of a new group of insulating materials consisting of silico-organic compounds and the creating of insulating materials with higher thermostability.
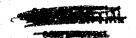
1. The fundamental work of Kurchatov, Kobeko, and others, dedicated to a detailed study of Rochelle salts, permitted the establishment of a series of rules which, to a large degree, explain the nature of their abnormal polarization. A group of dielectrics were also uncovered--isomorphous crystals containing Rochelle salts--having characteristics similar to Rochelle salts in regard to their spontaneous polarization and dielectric hysteresis.

These materials were called piezoelectrical.

Kurchatov first presented the theory of piezoelectric polarization which qualitatively explains the established rules. The theories of piezoelectricity, however, are not completely substantiated as yet. Neverthele , the viewpoint of Kurchatov and others, in which it is possible to rotate polar molecules in a solid substance, was very fruitful. It was developed further by clarification of a series of rules which were found for commercial dielectrics (fibrous materials, oleowax, halowax, etc.).

2. A good deal of the work carried on in the recent years by Soviet scientists (Bul, Skanavi, Gol'dman, Barzakovskiy, Bogoroditskiy and others), was dedicated to the study of dielectric polarization and losses of polycrystalline dielectrics, produced as a result of reactions in the solid state occurring at high temperatures.

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The most interesting of these projects pertains to dielectrics which contain titanium dioxide in the crystalline form of metallic rutile or titanate of the second group of Mendeleyev's periodic system.

The reason for the high dielectric coefficient of rutile (TiO_2), known from 1902, and perovskite ($CaTiO_3$), first established by Soviet physicists, was explained by their theoretical work (Skanavi).

In complex crystals, as in rutile and perovskite, neither Born's nor Clausius-Mosotti's formulas can be used to calculate the dielectric coefficient. Born's formula is based on the fact that the local field is equal to the average macroscopic one. In Calusius-Mosctti's formula, the internal field should be equal t the Lorentz field ($\frac{4\pi I}{3}$, where I is the electrical moment of a unit volume). Calculation of the internal field in the crystal lattice can be made in the first approximation if it is based on the so-called "point" model of an ionic crystal (point ions, which acquire dipolar moments due to the field). A method of calculating the internal field, based on Lorentz's method, leads in the end to the following general equation for electronic polarization in place of the Clausius-Mosotti's equation.

$$\frac{\varepsilon-1}{\varepsilon+2} = \frac{4\pi N}{3} \frac{\sum_{j=1}^{m} n_j \alpha_j + \frac{1}{2}\sum_{jk=1}^{m} \alpha_j \alpha_k (n_k c_{kj} + n_j c_{jk} - n_k c_{jj} - n_j c_{kk}) + O(\alpha^3)}{1 - \sum_{j=1}^{m} \alpha_j c_j + \frac{1}{2}\sum_{jk=1}^{m} \alpha_j \alpha_k (c_{jj} c_{kk} - c_{jk} c_{kj}) + O(\alpha^3)}, \quad (1)$$

where ε is the square of the index of refraction, N is the number of molecules in one cu cm of the crystal, α_j is the electronic polarizability of the jth ion, n_j the number of j ions in the molecule, m is the number of ions of different geometrical distribution in the lattice, C_{jj}, C_{jk} and C_{kj} are the so-called structural coefficients of the internal field, dependent only on the geometry of the lattice and determined by the given polarizability of the ions and the given external field supplementing the Lorentz internal field which is created by the polarized ions which surround the ion in question. $O(\alpha^3)$ designates the small terms having three and more multiples of the polarizability. If all the structural coefficients are equal to zero, then the above formula becomes the formula of Clausius-Mosotti,

$$\frac{\varepsilon-1}{\varepsilon+2} = \frac{4}{3}\pi N \sum n_j \alpha_j . \quad (2)$$

The calculated structural coefficients for rutile and perovskite lattices show that formula (1) in contrast to the Clausius-Mosotti formula, is substantiated fully by experiments. With infrared and lower frequencies, it is necessary to take into account, in addition to the electronic polarization of the ions, the displacement of positive ions relative to the negative. In this case, formula (1) for rutile appears as follows, if the small terms are disregarded:

$$\frac{\varepsilon-1}{\varepsilon+2} \simeq \frac{4\pi N}{3} \cdot \frac{\alpha_1 + 2\alpha_2 + \alpha_i}{1 + |c_{22}|\alpha_2 - c_{12}\alpha_i} , \quad (3)$$

where α_i is the polarizability of the ionic displacement, relative to a titanium ion. It is clear from (3), that even with the introduction of small α_i, ε abruptly increases, since the numerator increases and the denominator decreases. The physical nature of this effect consists of the fact that with ionic displacement there arises a large additional internal field in the same direction as the external field, which aids polarization. Because of this, a small polarizability of ionic displacement (α_i) leads to a high value of dielectric coefficient.

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It can be considered that the high dielectric coefficient of crystals of the rutile, and rutile and perovskite type, is greatly dependent in the first place on the high electronic polarizability of the oxygen ions. With a high density, this results in a high index of refraction in conjunction with a large additional internal field, directed toward the external field, and with an abruptly rising dielectric coefficient with the coefficient the change from light to infrared frequencies (from 7.3 to 173 for rutile), even with small ion displacement.

An outstanding achievement of Soviet physicists (Bul and Gol'dman) was the discovery of the extraordinarily high dielectric coefficient (ε equals 1,000 - 2,000), which passes through a sharp maximum when the temperature is increased, and dielectric hysteresis of barium metatitanate ($BaTiO_3$). Detailed investigations of the characteristics of this type of dielectric disclosed a new and very interesting type of dielectric polarization. This polarization is similar to the piezoelectric effect but is distinguished from it by a high value for ε in a very wide temperature range (from temperatures of liquid helium to plus 250 to 300° C). The extraordinarily high dielectric coefficient of barium metatitanate and also its sharp dependence on the temperature and the voltage of the electric field open up many possibilities for various applications in electricity and radio. The theoretical treatment of the polarization mechanism of barium metatitanate and piezoelectric effects was later developed by Ginzburg. He showed that a phase transition of the second order, occurring at a definite point (Curie point), can cause the dielectric coefficient to tend toward infinity at this temperature, if, in this transition, spontaneous polarization disappears. Roentgen's investigation of the barium metatitanate structure, at temperatures above and below the Curie point, and measuring the dependence of the thermal capacity on the temperature, showed that in barium metatitanate, at temperatures which correspond to the sharp maximum ε (around 80° C), the phase transition of the second order can take place.
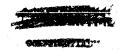
Investigation of materials of the system TiO_2 - BaO (Skanavi) showed that a change in the relation TiO_2/BaO shifts the Curie point and lowers the dielectric coefficient. In barium tetratitanate ($4\ TiO_2 \cdot BaO$) $\varepsilon \doteq 30$ and changes very little with temperature, making it possible to use it for temperature-stable condensers. The work on the dielectric characteristics of rutile and titanates uncovered a wide range of practical products which were developed during the war and which are being developed now. The ceramic condensers which possessed these given characteristics were obtained by combining titanates of various crystalline structures, having different dielectric coefficients and temperature coefficients. Rules were established and substantiated, by Roentgen and other investigators, which determine the characteristics of the combined poly crystalline material (Bul, Skanavi).

Dielectric losses in polycrystalline dielectrics, which were also studied very intensely, depend on the condition and quantity of the vitreous layer.

3. The work of Soviet physicists (Kobeko, Kuvshinskiy, Zhurkov, Shishkin, G. Mikhaylov and others) in the field of dielectric characteristics of amorphous bodies was fruitful not only with respect to the theoretical explanation of the processes occurring in an amorphous body, but also from the practical viewpoint.

Investigations on the relation of the loss angle and dielectric coefficient, conducted over very wide temperature intervals for a whole series of supercooled liquids containing polar molecules (glycerin, phenolphthalein, isobutyl, alcohol, etc.), showed that the loss angle passes through a clearly expressed temperature maximum. They also showed that the dielectric coefficient changes with temperature similarly to polar liquids. This was found at temperatures in which the substance was found in a solid--amorphous condition. An increase in frequency shifts the temperature maximum toward higher temperatures, which also takes place in polar liquids. Recently it was shown (G. Mikhaylov) that in solid-amorphous polymers containing polar groups the loss angle also has a second weaker temperature maximum in the low temperature region.

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All this definitely substant.ates the possibility of rotating polar groups in solid substances.

Further work showed that the chief and basic sources of dielectric losses in polymers were polar molecules, polar radicals or polar groups. If they are not held by the polymer, then the dielectric losses in it are very small. A clear example of this is polystyrene which has insignificant losses. The least contamination of polystyrene by polar substances will suddenly increase the loss angle and gives the whole process the evident character of dipolar loss.

Research work on the mechanical characteristics and viscosity of amorphous bodies led to the establishment of some interesting rules. It was illustrated that the curves showing the dependence of electrical conductivity, viscosity and time of dielectric relaxation on temperature are similar to each other. (The time constant of dielectric polarization was evaluated approximately as $1/2\pi\nu$, where ν is the frequency corresponding to the maximum product ϵ tg δ at the given temperature). The congruence between the indicated relationships brought to mind the existence of the deep connection between dielectric and mechanical relaxation of an amorphous body.

The presence of this connection was substantiated by parallel measurements of the dielectric coefficient and plastic deformation for amorphous bodies (Kobeko, Kuvshinskiy, and others).
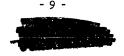
Thus, one can assume that the displacements and reversals of dipolar groups are related to the displacements and reversals of whole molecular groups caused by the plastic deformation.

Research on amorphous conditions made possible the development of new high-quality insulating materials. One of the first of such materials was the Soviet polystyrene which has very low dielectric losses (a loss angle of 0.5 - 1' at high frequencies), very high volumetric resistance, and other valuable characteristics, in particular ease of manufacture.

The study of dielectric and mechanical characteristics of rubber (Kobeko, Ponomarev) led to the development of an unusual sulphur-free "ebonite-eskapon" which is the product of polymerization of rubber and which has great thermostability, is easily workable, and has a comparatively small loss angle (1 - 2' at high frequencies). This material in all respects surpasses common ebonite containing sulfur. Each atom of sulfur is attached to 2 atoms of carbon and at the same time, under the influence of carbon and hydrogen atoms is strongly polarized, forming a permanent electrical moment. The mobility of the hydrocarbon chain in rubber makes it possible to form a polar "sulfur bridge" to achieve the rotational oscillations which occur in thermal agitation. The electric field orients the "sulfur dipoles." The process of establishing this orientation at high frequencies leads to clearly expressed dipolar losses. The absence of sulfur in eskapon and the high degree of its polymerization appear to be the basic reasons for the small dielectric losses of eskapon.

Soviet scientists have been working for some time in the field of theory of dielectric losses. By broad and systematic studies it was established (Lazarev and others) that Debye's classical theory of dipolar losses is applied qualitatively to a majority of the amorphous commercial dielectrics above their solidification point (for example, oils, lacquers, compounds), but this theory does not give a quantitative confirmation, experimentally, for the indicated dielectrics. In connection with this, a series of viewpoints were developed on the mechanism of dielectric losses in various classes of dielectrics which has greatly aided the development of new dielectrics with small losses.

Most of the work relating to the theory of dielectric losses in solid dielectrics which has been published in foreign literature has a purely phenomenal

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character. The author presents this or that aspect of the function for current drop with time and, using the known principle of superposition of currents in dielectrics, with the aid of more or less exact and cumbersome calculations, obtains an expression for ε and tg δ of the dielectric, depending on frequency.

Soviet scientists made attempts to develop theories of dielectric losses, based on specific structural characteristics of the class of dielectrics under investigation.

4. The measurement of dielectric losses in crystalline dielectrics (Bogoroditskiy and Malyshev) established that the dielectric losses in crystals have a purely ohmic character (conductivity losses). On the other hand, in a series of amorphous dielectrics, which do not contain polar groups and molecules, losses were uncovered at high frequencies which were not of the conductivity type (the work of Kobeko-Aleksandrov, Skanavi, Bogoroditskiy, Malyshev, Fridberg). The presence of these losses is of great practical significance since they limit greatly the use of a whole series of amorphous dielectrics (glass, chiefly) for high frequency insulation. The work of Soviet physicists (Kobeko, Skanavi) in studying the mechanism of dielectric losses in glass led to the discovery of a new group of effects in solid-amorphous dielectrics which were similar to those produced by the rotation of polar molecules. This new group of effects is caused by the gradual shifting of weakly connected ions or charge groups.

The movement of such charged particles under a constant voltage brings about a decreasing absorption current with time, and with voltage, brings about dielectric losses of the relaxation type.

The absorption current in a solid dielectric with the indicated ionic movement should, as shown by calculations, fall with time according to a simple exponential law, whereupon the time constant of the current drop is proportional to the relaxation time of the weakly connected ions. It is equal to $\tau \cong \frac{e^{U/kT}}{2\nu}$, where U is the activation energy, ν -natural frequency of oscillation. However, to describe the experimental data more adequately, we may use an exponential function of the form I equals $A(t + \theta)^{-n}$ which reflects the process in the limited time interval (A, θ and n are constants).

This discrepancy is explained by the fact that in a real dielectric there are a number of groups of ions with different activation energies, i.e., with different relaxation periods. In addition, a number of other processes occur (e.g., accumulation of space charge) whose combination complicates the law defining the drop in absorption current.

The use of the exponential function of current drop leads to cumbersome mathematical computations and does not help very much in explaining the mechanism of dielectric losses. The exponential function of the drop reflects one of the processes (in many cases the prevailing one) existing in the dielectric. The theory of losses, built up primarily on the use of this function, even though it cannot claim to be rigid and complete, connects, as does Debye's for polar liquids, the values of the dielectric losses in a solid-amorphous dielectric with its molecular constants.

The work of Soviet physicists, dedicated to the use and development of the theory of losses in solid-amorphous dielectrics (chiefly in glass) helped to create new viewpoints on their mechanisms and, to a greater degree, contributed to the discovery of new methods for obtaining glass with small dielectric losses.

A series of interesting facts were established (the work of Kobeko, Skanavi, Martyushov, Gladkikh and others) relating to the influence of the composition of the glass on its dielectric losses. These facts concern: (1) the "neutralizing" effect wherein the detrimental effect of one alkaline metal can neutralize the introduction of the oxide of another alkaline metal (this neutralization is so great that an alkaline glass can have as small a loss angle as pure glass without extraneous ions); (2) the "crystallizing" effect as a result of which crystallization of the amorphous dielectric (sugar, glass) abruptly lowers its loss angle at high frequencies, etc.

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This work permitted the classification of dielectric losses in glass, which can be considered as consisting of three parts: (1) conductivity losses which appear at low frequencies and high temperatures, (2) relaxation losses which appear at high frequencies and (3) structural losses, whose loss angle does not depend on the temperature. The latter appear at high frequencies and low temperatures. Their mechanism is not sufficiently clear as yet.

C. New Insulating Materials

The work of Soviet physicists, chemists, and technologists in the study of the dielectric properties of various types of materials has served as a theoretical basis for obtaining new insulating materials with high insulating properties.

This concerns first of all the development of new inorganic materials (glass and ceramic) whose application plays an especially important role in high frequency techniques, since they show considerably smaller dielectric losses than many organic materials, and very high thermostability.

The research conditions in our country are very favorable for complex projects in which the activity of the physicists is in close coordination with that of the chemists and the technologists. Electric insulation is the very field of science and technology where such cooperation is indispensable.

Ceramic materials exist in crystalline and amorphous phases. It may be that the dielectric losses in ceramic materials are, in the first approximation, the sum of the losses in each of these phases.
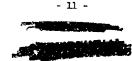
As was indicated above, losses in crystalline dielectrics are due to conductivity, and therefore are very small at high frequencies. Consequently, the main source of dielectric losses in ceramic materials is vitreous interstratification.
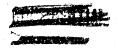
The series of rules which has been established for dielectric losses in glass permits a systematic approach to the selection of the composition and structure of ceramic material with small dielectric losses. The principles for obtaining such material are as follows: (1) the material must have a fine crystalline structure with a minimum of vitreous interstratification; (2) the vitreous interstratification, as far as possible, must not contain alkalies, or the effect of these alkalies must be neutralized by heavy /metallic/ oxides.

In accordance with these general principles, a series of high-frequency ceramic materials with small dielectric losses has been developed. The first material of this group, produced in the Soviet Union and used widely, is a ceramic material based on the mineral pyrophyllite (Vaneyev, Popov). A mixture of pyrophyllite and clay possesses a number of properties that are of great industrial importance, including great plasticity up to the time kilning takes place, which permits the use of all methods of ceramic manufacture (machine molding, extrusion, pressing) which have a long kilning interval. In addition, ceramic materials with a pyrophyllite base show, in comparison with ordinary porcelain insulators, small losses at high frequencies (8 - 12 minutes at a frequency of $\sim 10^6$ cycles).

By putting heavy /metallic/ oxides in insulating porcelain instead of feldspar it has been possible to "enrich" it considerably and to obtain the so-called radio porcelain, not inferior to pyrophyllite in dielectric properties and technologically close to common porcelain (the work of Bogoroditskiy and Fridberg).

Work on obtaining ceramic materials with very small losses and other special properties (e.g., a high dielectric coefficient and stability during temperature changes--for condenser ceramics) has been carried out intensively.

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A series of high-frequency materials with small losses were developed, based on aluminum oxide (Bogoroditskiy, Odelevskiy, and others). These materials have very small loss angles at high frequencies (ε equals 1 - 3').

Special attention has been given to the preparation of ceramic materials for high-frequency condensers. Bogoroditskiy, and others, prepared "tikond," a ceramic material based on titanium dioxide and clay with a high dielectric coefficient ε equals 60 - 70 and a relatively large negative temperature coefficient of its variation:

$$\frac{1}{\varepsilon} \frac{d\varepsilon}{dT} \cong - 5 \cdot 10^{-4} \text{ 1/degree}$$

This material is an appropriate dielectric for special condensers which compensates for frequency variation during temperature change in radio circuits, due to the negative temperature coefficient of the capacitance.

During the war the importance of high-frequency crystalline ceramic materials increased even more, due to their low cost and abundant supply of the ore used to produce them, and also the possibility of regulating the dielectric coefficient and its temperature coefficient by varying the composition and structure of the crystalline phase of these materials.

A new ceramic material for compensating radio condensers based on calcium and magnesium titanates is "tidol" (Skanavi), with a still higher negative temperature coefficient of the dielectric coefficient than tikond ($\frac{1}{\varepsilon} \frac{d\varepsilon}{dT}$ = -10 $\cdot$ 10^{-4} 1/degree), and a high dielectric coefficient (ε equals 70 - 80). The loss angle for tidol is 2 - 3'. A series of materials based on magnesium titanates were developed (Vul, Skanavi, Barzakovskiy, Bochkarev). These ceramic materials were intended for radio condensers of large and small reactive power. They show a very small loss angle (δ equals 0.5 - 1' at high frequencies), which is largely independent of frequency and temperature; a dielectric coefficient ε equals 14 - 16; and, what is especially important, stability of dielectric coefficient at high temperatures:

$$\frac{1}{\varepsilon} \frac{d\varepsilon}{dT} = + (0.4 - 1.3) \cdot 10^{-4} \text{ 1/degree}$$

A material has been prepared based on titanium dioxide and clay with aluminum oxide, called "tiglin" (Smolenskiy), also very useful in radio condensers. The discovery of the possibility of regulating the dielectric coefficient and its temperature coefficient in titanium ceramic materials by application of Likteneker's logarithmic (Vul, Skanavi) law, is of great importance. In combining crystalline materials of different structure, it is possible to avoid the formation of new structures in the caking process by special methods. In these cases, it is possible to calculate beforehand the dielectric coefficient of the combined material by the dielectric coefficient components:
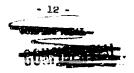
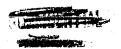$$\lg \varepsilon = x \lg \varepsilon_1 + (1-x)\lg \varepsilon_2,$$

where ε_1 and ε_2 are the dielectric coefficients of the components and x is the volume concentration of the first component. Differentiating this equation with respect to temperature gives

$$\frac{1}{\varepsilon} \frac{d\varepsilon}{dT} = x\frac{1}{\varepsilon_1} \frac{d\varepsilon_1}{dT} + (1-x)\frac{1}{\varepsilon_2} \frac{d\varepsilon_2}{dT} ,$$

i.e., the temperature coefficient changes linearly with concentration.

By combining materials with positive and negative temperatures coefficients ε , it is possible to obtain a given dielectric coefficient with a great degree of accuracy, and, what is especially important, a given temperature coefficient of the dielectric coefficient.

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By this method many condenser ceramic materials have been developed with various temperature coefficients ε from $+1 \cdot 10^{-4}$ to $-12 \cdot 10^{-4}$, including temperature coefficients ε near zero (Skanavi, Stepanov, Voronkov, Bogoroditskiy, Smolenskiy, Odelevskiy, Nekrasov, and others).

Following the discovery of the unusually high dielectric coefficient of barium metatitanate (Vul and Gol'dman), ceramic crystalline dielectrics based on barium metatitanate were manufactured with a super-high dielectric coefficient, i.e., from 700 to 1,500 at room temperature (Skanavi, Voronkov, Odelevskiy). Work has been done on the use of those materials in various fields of electrical and radio engineering. Crystalline ceramic dielectrics have been produced based on barium tetratitanate ($4\ TiO_2 \cdot BaO$) and similar compounds (Skanavi) with a very small loss angle at high frequencies, a dielectric coefficient of about 30, a temperature coefficient approximating zero, and a very high volume resistivity ($10^{15}-10^{16}$ ohm/cm). These dielectrics made it possible to manufacture thermostable ceramic radio condensers of high specific capacitance.

There have also been a number of achievements in the Soviet Union in the field of application of glass as an insulating material.

First of all, there are the special types of glass used in radio engineering, (e.g., for high-power radio tubes). Glass No 23 and Glass No 46 have small dielectric losses, in addition to the necessary technological properties. Potassium pyrex (Bogoroditskiy and Friberg) has been manufactured with a very small loss angle at high frequencies and with thermostability as well.

Chernyak, Aslanova, and others have solved the basic problems involving glass fibers and glass fabrics in the heatproofing of electrical insulation. Further research is necessary here, especially in the selection of more suitable glass.

Andrianov, Tareyev, Chernyak, and other Soviet scientists have done considerable research on the thermostability (heatproof qualities) and heat conduction of insulation; furthermore, Mikhaylov, Bogoroditskiy, and others are studying the hygroscopicity of dielectrics.
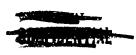
The production and application of glyptal lacquers have greatly increased; coatings of these lacquers possess higher heatproof qualities than the coatings of shellac and asphalt lacquers. In addition, the dielectric properties of glyptal lacquers are of a comparatively high order.

Asphalt lacquers, which are replacing scarce shellac, are again being widely produced and employed in industry, especially for use in electrical machines.

Among the new plastics, those deserving greater attention are polystyrene and eskapon, already mentioned. Andrianov and Gribanova have successfully developed primarily new electrical insulating materials on the basis of silicone compounds. These materials, liquid and solid, combine within themselves the properties of organic compounds (plasticity, elasticity, etc.) together with high thermostability (up to 300° C). The indicated materials were developed as a result of extensive studies in a new branch of science, namely the chemistry of silicones (by Andrianov). This short account does not exhaust the list of developments seen in recent years in the field of new insulating materials.

D. Rupture of Dielectrics

We will now examine the studies of Soviet physicists on dielectric rupture. The puncture voltage for insulators depends on the electrical stability of the insulating material and, to the same extent, on its structure, which determines the distribution of the electric field in the insulation and the conditions of heat developing. Rupture should be studied not in models alone, but under practical operating conditions.

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In the Soviet Union the theory of rupture was begun 20 years ago (Semenov, Fok, Bragin, and others). Broad experimental studies established the factors characterizing thermal and electrical rupture of insulation. Criteria were established for classifying rupture in each separate case, in a series of dielectrics, and research was carried out on the characteristics of rupture (Bragin and others).

Fok, Semenov, and others first gave a strict theory of thermal rupture which was successful in practice.

1. Thermal Rupture (Shock) of Dielectrics

Thermal rupture usually involves two groups of problems, interesting from the viewpoint of application of this theory. The first group determines the breakdown or puncture voltage, which in the case of thermal rupture, can be treated as that maximum voltage (critical voltage) beginning with which the stationary state is impossible. When the critical voltage is attained, continuous heating begins in the dielectric, which after continuous use for some time leads to thermal rupture. The second group determines the "time of rupture"; that is, the time it takes the dielectric to break down after reaching the critical voltage. Both groups of problems are of very great engineering interest because:

a. The calculation of the critical voltage of thermal rupture makes it possible to select properly that quality and construction in the insulation which assures a full useful life.

b. The calculation of the "time of rupture" at voltages higher than the critical permits one to calculate, for any given selection of the insulation, stability versus short-time excess-voltage. The first group has been solved and the results have been used for a number of years. The second group has been solved basically in recent years.

Thermal rupture in a dielectric is due to the fact that the generation of heat from dielectric loss (or conductivity at constant voltage) increases as the dielectric is heated. For most dielectrics, the liberation of heat depends upon temperature in a limited interval according to the following exponential law:

$$Q = Q_0\, e^{\alpha \cdot (T - T_0)}$$

where T and T_0 are temperatures and α is the temperature coefficient of conductivity or the tangent of the angle of loss.
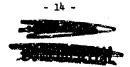
Thermal rupture is solved by integrating ordinary well-known equations of heat conduction, such as:

$$c\rho \frac{\partial T}{\partial t} = K \Delta T + Q .$$

where c is the specific heat of the medium, ρ is the density, K is the heat conductivity and $Q = \gamma E^2$ is the specific amount of heat liberated (γ is the conductance and E is the field intensity) or for the uniform case often met in practice:

$$c\rho \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2} + Q$$

In the solution of the first group of problems (of finding the critical puncture voltage), only the equilibrium state is examined ($\frac{\partial T}{\partial t} = 0$) and hence time is naturally excluded from the examination.

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The differential equation

$$K \frac{\partial^2 T}{\partial z^2} + Q = 0$$

serves basically to calculate the critical voltage.

The transition of the dielectric from the thermal state of equilibrium to the nonequilibrium state (during increases in the applied voltage), which appears at the beginning of thermal rupture, is characterized by $\frac{\partial E}{\partial T_m} = 0$, where E is the field intensity and T_m is the maximum temperature of heating for a given voltage.

When $\frac{\partial E}{\partial T_m} > 0$, we have the equilibrium state; and when $\frac{\partial E}{\partial T_m} < 0$, we have the nonequilibrium state of the dielectric. The equation $\frac{\partial E}{\partial T_m} = 0$ thus appears as the condition necessary for rupture. Solving the above differential equation with the proper boundary conditions and using the necessary rupture condition formulated above, we can find the expression for the puncture (critical) voltage of thermal rupture. For example, for a uniform alternating field intensity, we have:

$$U_{puncture} = \sqrt{\frac{60.5 K}{f a \varepsilon \tan \delta}} \cdot 10^6 \varphi \; (C)$$

where ε and δ are the dielectric permeability and angle of loss, respectively, of the dielectric at ordinary temperatures; f is the frequency; φ (C) is a rather complex function, whose approximate value is

$$C = \frac{K_1 \lambda h}{K(K + \lambda d)}$$

(K and K_1 are the heat conductivity, respectively, of the dielectric and electrode; h is the half-width of the dielectric; d is the width of the electrode; λ is the coefficient of external thermal conductivity; and a is the temperature coefficient of conductivity or the tangent of the angle of loss).

This formula, like the previous one (the case of one-sided cooling, a cylindrical condenser, etc.), has the great advantage that all quantities entering the right side of the equation can be accurately known. Because of this, its use in any practical case does not, theoretically, bring about any difficulties. It is only necessary to calculate correctly the cooling conditions or laws.
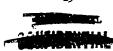
Investigations established that if the cause of the rupture is heat, then for sufficiently slow increase in voltage the experimental value of the puncture voltage corresponds well with the theoretical calculated value. For rapid increases in voltage, the experimental value of the puncture voltage exceeds the theoretical value.

For most dielectrics thermal rupture is also dependent upon external factors; in particular, upon frequency and temperature.

At high frequencies the rupture of most dielectrics has a clearly expressed thermal character. Only certain dielectrics (namely; quartz, the better sorts of mica, special ceramic materials), which have an insignificantly small angle of loss at high frequencies, have a complex mixed type of rupture.

At high temperatures, many dielectrics (glass and porcelain) suffer thermal rupture even at low frequencies.

Finally, many other dielectrics suffer thermal rupture at low temperatures and low frequencies. To this inferior group belong all lacquers, compounds, fibrous materials, and many plastics.

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Thus the theory of thermal rupture and the practical formulas for calculating puncture voltages permit one to select consciously and deliberately the proper insulations and to develop basic technical norms or standards for insulating materials.

A series of special projects were mapped out to calculate and design insulators for heavy machinery, antennas, cables, condensers, basically by the theory of thermal rupture. As a result of this work standard norms were established for the electrical characteristics of lacquers and compounds (insulation of electrical machines by the author Skanavi), ceramic materials (antenna insulators by Gaylish), oils and paper (cable insulators by Bragin) etc.

Gaylish's work exploited the theory of thermal rupture to permit further practical developments.

All these investigations disregarded the more complex problem concerning the time variation of thermal rupture. All calculations were made for the simplified case where insulators were subjected for long time intervals to constant voltages. The coefficient of "accumulation" of the insulator, which is determined not only by the possibility of thermal rupture for prolonged operation of the insulation subjected to ordinary operating voltages but also, mainly, by its stability against alternating voltages, cannot be sufficiently and accurately determined by our theory of thermal rupture, which makes the simplifying assumption that the voltage is applied for any length of time desired.
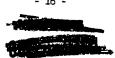
In recent years Grinberg, Kantorovich, and Lebedev finally developed a method of calculating thermal rupture which takes the time factor (the second group of problems indicated above) properly into consideration.

Differential equations that describe the heating process in dielectrics are extremely complex and are not amenable to exact integration. Even in the simpler uniform case, it is necessary to integrate two sets of differential equations with partial derivatives of the second order, none of which appear to be linear. At first it was solved by approximate numerical integration for specific cases.

However numerical integration for every individual case is extremely time-consuming because of very unwieldy computations that are necessary.

Therefore, an approximate theory was developed to obtain without a great loss of time, basic . lations which are sufficiently accurate for practical purposes. The crux of the method is that the determined physical expressions contain a law for the temperature distribution within the dielectric and electrode. If a parabolic law of temperature distribution is assumed in dielectrics and sufficiently large electrodes, then the system of equations is considerably simplified in comparison with the first (the system obtained is an ordinary set of differential equations of the first order). The calculation work is greatly shortened, but the integration still cannot be fully carried through and therefore numerical integration must again be adopted. The problem is solved analytically in this case if, within the electrodes (external heat insulation), the temperature is assumed to be distributed not parabolically but linearly. It may seem that the indicated law is conserved in the greater part of the process, at least if the electrodes are not very thick. The length of the previous part of the process appears as a small part of the entire period which is needed for the development of the rupture.

The theoretical rupture time, that is calculated by the indicated approximation method, is in sufficiently good correspondance with experiments. The rupture time is found from the necessary condition that the dielectric temperatures be equal to infinity. This condition can be satisfied only when the applied voltage is greater than the critical voltage of thermal rupture, that is, a stationary state cannot exist in a dielectric.

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The result of calculation for a flat condenser can be written in the following simplified form:

$$t_{puncture} = \frac{C_1 \rho_1}{0.24 \cdot a \sigma_0 E^2} \, \varphi(b),$$

where C_1 is the heat capacity and ρ_1 is the density of the dielectric, and phi equals:

$$\varphi(b) = \int_0^\infty \frac{d\zeta}{e^\zeta - b\zeta} = 1 + \frac{1}{4} b + \frac{2}{27} b^2 + \frac{3}{128} b^3 + \frac{24}{3125} b^4 + \ldots$$

and

$$b = \frac{6\beta}{3 - \beta} \cdot \frac{1}{Bh^2}$$

$$\left(\beta = \frac{\mu}{2 + \mu} \text{ for } \mu = \frac{\lambda h K_1}{K(K_1 + \lambda d)} \text{ and } B = \frac{0.24 a \sigma_0 E^2}{K} \right).$$

σ_0 is the dielectric conductivity when the surrounding temperature and the other expressions are the same as above.

2. Electrical Rupture (Breakdown) in Solid Dielectrics

Soviet physicists are working extensively on electrical rupture or puncture.

The mechanism of electrical rupture in dielectrics is not completely clear as yet. The first, but erroneous, notion expressed was that currents, during electrical rupture of solid dielectrics, develop mainly because of ionization.

Our later ideas on the mechanism of electrical rupture showed two clearly distinguishable stages of development: prequantum and quantum-mechanical.

The old (prequantum) theories led to calculated magnitudes of puncture voltages that exceeded the experimental values. Contemporary (quantum-mechanical) theories give correct orders of magnitude of the puncture voltages, but not sufficiently good correspondence with experimental data. Therefore, it is difficult to select the theory which is closest to reality.

The lack of satisfaction with the old theories is explained by the errors of the basic notations and by the fact that they were developed by classical rather than quantum-mechanical means.
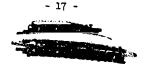
All theories regard electrical rupture as fusion in the dielectric (the simpler case usually examined in theory is the crystal dielectric).

Thus, both thermal and electrical rupture can be considered to lead to the same thing; that is, to the thermal rupture of the dielectric. The processes leading to this result are sharply different.

In thermal rupture, the dielectric is strongly heated by the current, increasing with temperature, which in turn brings about a further heating of the dielectric due to this very current. The determining factor in this process is the ion current, which increases sharply with temperature but grows comparatively little under increasing field intensity.

During electrical rupture, the disturbance in the dielectric is of a thermal nature and is brought about by the increase in current with increasing field intensity.

The determining factor in this process is not the ionic current but the electrical current, which is insignificantly small for weak fields but which rises sharply with increase in field intensity for strong fields. The electron flow or current in the dielectric depends comparatively little upon temperature and therefore any electrical rupture develops only with increasing field intensities.

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The electron current in crystal lattices can be of three varities: purely electronic, Dirac, or composite. The energy distribution (spectrum) of the crystal lattice of a dielectric is characterized first by the great width of the forbidden region dividing the conductivity zone and the normal zone and second by the almost complete absence of electrons in the conductivity zone. Under normal conditions, therefore, the electron current in the dielectric is insignificantly small.

Between the normal zone and the conductivity zone in all real dielectrics, there are distributed localized discrete levels which can depend on: (a) foreign atoms scattered in the lattices, (b) unfilled corners of the lattices, (c) mechanical disturbances in the lattice, etc.

The electrons in these planes, in contrast to the electrons in the proper planes, are limited in their motion to very narrow regions within the crystal. To bring about an electron current in a crystal dielectric, it is necessary to enrich the conductivity zone with electrons and to deprive the normal zone of electrons. These conditions in the presence of localized discrete intermediate planes in the prohibited region can be filled not only simultaneously but also individually. The motion of electrons from the localized planes to the conductivity zone ensures a purely electron current.

Finally, the motion of electrons from the normal zones to conductivity zones produces a composite electron-Dirac current.

Thus, to excite an electron current in the dielectric, its ionizing agents must be excited to ensure even one of the above indicated electron motions. A high temperature and a strong field intensity are such ionizing agents. The first of these ionizing agents -- high temperature -- appears effective only for a small width of the prohibited band, that is, in the case of semiconductors. The dielectric would have to be heated to a very high temperature, considerably greater than its melting point, in order to obtain in it a noticeable electron current in a weak field.

The ionizing possibility of a strong field, on the other hand, is sufficiently effective for a dielectric. Ionization is dependent upon deformation of the energy distribution spectrum of the lattice, which deformation is brought about by the application of a strong field and is expressed in the inclination and widening of the zones. In the ionization process, the first effect is the basic factor. The indicated deformation of the levels makes possible the vertical (with energy loss) and the horizontal (without energy loss) motion of electrons.
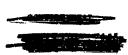
Horizontal motion is similar to the escape of electrons through a potential barrier; vertical movement is similar to excitation.

Therefore two mechanisms of ionization must be distinguished: (1) impact ionization (vertical motion) and (2) escape ionization (horizontal motion).

The contemporary theories of electrical rupture can be divided into two groups: (1) the theories based on the mechanism of impact ionization and (2) the theories based on the tunneling effect.

The theories of impact ionization do not lead, in contrast to the old theories, to the avalanche-like growth of current with time since not only the freeing process but also the fixi _ process is considered in electrons. Now, the present theories of impact ionization in a solid dielectric do not substantiate "hardening" in thin layers, and the phenomenon was not encountered in experiments.

The work of Soviet physicists to discover the nature of the electrical rupture mechanism has uncovered some experimental facts that, on the one hand, substantiate the unusual role of the electron current during electrical rupture of

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dielectrics; and that, on the other hand, show preference for the theory of the tunneling effect in comparison with the theory of impact ionization (Vol'kenshteyn).

The tunneling mechanism of electrical rupture is characterized by almost complete independence of temperature and by its sudden appearance. These peculiarities are indirectly substantiated by the experimental data of Soviet scientists.

The above-described scheme of the nature of dielectrics and electrical rupture is based on the "zonal" theory, which has been minutely developed for metals. The application of this theory to dielectrics appears only as a rough approximation to actuality.

In 1936 - 37 Ya. I. Frenkel developed a different concept of the nature of dielectrics. According to his version, a crystal dielectric is treated as a compressed gas in which every atom has its normal complement of electrons. External surface electrons can be partly collected only when the crystal is excited. During absorption of light, one of the atoms may not only allow an electron to break away but also become itself excited. In a gas, the excitation state can pass from one atom to another during collision. In a crystal, this transfer of excitation can occur without impact because of intense interaction between adjacent atoms. Thus the excited state seems to be able to move among the atoms in some wave law. Consequently, the excited state can be treated as certain fictitious particles which Frenkel called "exitons." The absence of a clearly expressed internal photoeffect in many crystals can be explained by the concept that when the light is quenched not "collectivized" electrons and Diracs are formed but so-called electrically neutral exitons.

Davydov developed a theory of gas rupture based on the fact that the ionizing impact of atoms with electrons precedes the excitation impact. Developing the stated concept of the dielectric as a compressed gas, Frenkel brought out a formula which gives the dependence of the electron conductivity of a crystal upon field intensity:
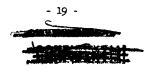
$$\sigma = \sigma_0 \cdot e^{\frac{\sqrt{q^3 E}}{kT}},$$

where q is the elementary charge and E is the field intensity. It is possible that further developments of this promising concept will make it possible to construct a new theory of electrical rupture in crystal dielectrics.

Actually, the electrical rupture appears in a group of dielectrics under corresponding conditions. The criteria of electrical rupture in the absence of thermal rupture are (1) independence of temperature, (2) independence of the time of duration of the applied voltage, and (3) disturbance of the dielectric at the position of the largest field intensity (most often at the edge of the electrode).

These conditions, however, rarely appear simultaneously and completely. Most dielectrics, depending on conditions, can be ruptured by heat as well as by electrical means. For example, during prolonged action of the voltage, for one and the same dielectric, thermal rupture can take place; during a short period, electrical rupture can take place. High temperatures and high frequencies, as was shown above, cause all dielectrics to undergo thermal rupture, etc. It is very essential, therefore, to establish not only the criteria of electrical rupture but also the conditions under which it will occur in any dielectric. Soviet physicists have played a great role in this work.

Very important (theoretically as well as practically) is the discovery by Soviet scientists (Vul and others) of special forms of electrical rupture; namely, incomplete rupture and gradual rupture. It was shown that if the dielectric (rock salt, glass, mica, etc.) is subject to the shocks of an impulse voltage, somewhat smaller than the puncture voltage, then the dielectric begins to collapse.

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However, this collapse is not complete; complete rupture in the dielectric results from shocks which leads to microscopic cracks, and sometimes even to visible cracks and other signs of breakdown, in the dielectric.

A succession of incomplete ruptures can lead to definite rupture at voltages almost one half as large as the normal puncture voltage. Such a gradual rupture was found in cable paper, bakelite-paper panels and micanit.

Gradual rupture develops in close connection with the gradual breakdown of the dielectric, because of not only incomplete ruptures but also boundary discharges. In the presence of boundary discharges, gradual rupture is possible for an alternating voltage of low frequency.

The danger of gradual rupture in insulators necessitates the renewed consideration of the construction, exploitation, and testing of high frequency installation, transformers, electrical machines, cables, and transfer lines. The rupture of insulators in all these installations has a gradual nature, except for direct lightning shocks. Incomplete rupture of the insulator can occur by shocks in an irrationally conducted insulation test, which will show up later in the post-test exploitation of the installations.

3. Rupture of Liquid Dielectrics and Gases

Soviet physicists are studying not only rupture in solid dielectrics, but also rupture in liquid dielectrics and particularly in gases.

The study of rupture in liquid dielectrics has not yet resulted in solution of its mechanism, but has explained many secondary effects (the role of gas, water, etc.) which usually complicate the picture of liquid rupture.

Soviet physicists have made great advances in the study of rupture in gases. Here the physics of dielectrics comes close to the physics of gaseous discharge.
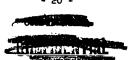
At present, special needs in the electrical industry have appeared in relation to obtaining nonaging, thermostable, high-voltage insulators. As such an insulator, compressed gas began to be used (gas-filled cable, condensers with compressed gas, etc.) These projects on rupture in gases are obviously of great practical value.

The influence of various factors upon rupture in inert gases (particularly, nitrogen) was minutely and systematically studied. The influence of pressure and temperature, forms of the electrodes, the intervals between the electrodes, exposure, etc. was also studied (the work of Vul, Gol'dman, Kovalenko, Parnas).

The electrical stability in various gases was intensively studied, particularly, with the objective of finding a gas of high electrical stability whose use would not necessitate such high pressures as in the use of nitrogen (the work of Fokhberh, Zanberz, Kovalenko and others).

The electrical stability of a gas is apparently connected with its molecular weight. Gases of low molecular weight have low electrical stability. On the other hand, heavy gases are characterized by high electrical stability. However, there is no direct functional dependence between molecular weight and electrical stability.

The study of the electrical stability in various gases established a series of laws, particularly the law that the first coefficient of ionization (ionization by electrons), occurring during rupture in a gas, does not depend (or only a little) on the individuality of the gas; furthermore, this study found a gas with great electrical stability (2.5 times greater than the electrical stability of air) whose use as an insulator, for example in high power condensers, would not encounter any difficulties. This gas was called "elegas" (Fokhberg and others).

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Later, these projects were further developed (Fokhberg, Zandberg). Precise study established that the first coefficient of ionization in various gases attains the same value in sharply different field intensities.

These field intensities, for which the quantity alpha attains one and the same value, in various gases have the same relation to the field intensity in air as the puncture intensities of these gases do to the puncture intensities of air. Thus it was simultaneously established that the development of gas rupture is chiefly and basically determined by electron impact ionization. The rupture voltage depends only upon the dependence of the first ionization coefficient upon voltage.

4. The Fight Against the Aging of Electrical Insulators

In insulation technology useful life is very important. A long life in many cases can be assumed only by special measures against aging.

The aging of insulation materials was first systematically studied by Vul and Gol'dman. The aging of insulating materials as influenced by high voltages depends on the following facts: (1) heating of the insulator due to increased dielectric losses, chiefly at high frequencies, (or due to higher temperatures at which the apparatus operates) leading to gradual thermal rupture of the material; (2) ionization of air gaps within the insulating material, which leads to local heating of the insulator, mechanical breakdown of the insulator due to spark discharges in the air gaps, and chemical breakdown of the insulator due to ozone and nitrogen oxides formed during ionization of the air gaps.
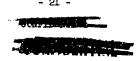
The first factor, gradual thermal breakdown of the insulator, eliminates the haphazard selection of materials which have suitable thermostability and sufficiently small angle of loss. In recent years the problem of thermostability in insulators was intensively studied by Soviet physicists and chemists. As a result of their work, insulating lacquers with higher thermostability (chiefly graphite lacquers) were developed and partially introduced into industry. Various types of asbestos materials (bands, paper) were developed and were soon in wide use in insulation technology, especially in high-voltage electrical machines. Along with this, a series of projects on practical applications of the theory of heat rupture soon established standards for the loss angle permissible in various materials to be used in electric machine construction, cable technology, and high-frequency work. These norms guarantee the standard life expected of these materials without internal heating. Work was begun in the use of glass fiber in the technology of cable and electric machine construction which is hoped to increase greatly the working temperatures and hence the power of machines and cables.

In this group are included industrial problems on heat conducting insulators, basically of asphalt and quartz, which have already found practical application.

The second factor that causes aging in insulators, namely ionization of air layers, was studied in great detail and systematically by Skanavi, Kononykin, and Bugel'. A method was developed for finding incipient ionization.

Aging in insulators is caused not only by the ionization of occluded internal air, but also by corona discharge on the insulator surface, which can take place at the edge of the insulating material and is not necessarily eliminated by the "monolithic" construction of insulators (compact without sharp projections that could serve as corona discharge points).

Control of corona was taken up by the Soviet physicists Ioffe, Vul, Gol'dman, Skanavi and others. Their work showed that the practical levelling of the field at the edge of the insulating material can be done by very simple means:

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by covering the edges of the material and surface of the insulator with a lacquer of high dielectric permeability or by covering with a semiconductive lacquer. The second process includes the use of carbon-black asphalts and carbon-black bakelite lacquers in heavy-duty electrical machines, where they are used in combination with asbestos semiconductive bands.

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